From optical graphene to topological insulator

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Outline

- Background: From solid state physics to Photonic Crystal
  - Photonic monolayer graphene materials
  - Multilayer photonic graphene materials
  - Dirac-cone photonic surface states
  - Probing photonic surface states by STEM
- Summary
1. Background

(1) Corresponding between disorder system for electrons and wave in random medium

Disorder electron system \[\rightarrow\] Wave in random medium

1984

Ballistic \[\rightarrow\] Diffusion \[\rightarrow\] Weak localization \[\rightarrow\] Anderson localization

(2) Corresponding between electron and wave system for periodic and quasi-periodic structures

Solid state physics (electron system) \[\rightarrow\] Photonic or phononic crystal

1987
Various applications based on photonic crystals

Cavity and laser

Waveguide

Optical fibers

Channel drop filter
Unusual features of wave in the band regions

Negative refraction, self-collimation, ultrarefraction

Some devices such as flat lens, splitter can be done
Recent progress in Condensed Matter Physics: graphene material

carbon atom
The physical properties of graphene materials

(1) The quasiparticle excitations around the Dirac point obey linear Dirac-like energy dispersion (Rev. Mod. Phys. 80, 1337 (2008)).

(2) Chiral tunnelling and Klein paradox, *Zitterbewegung*

(3) Edge states (Rev. Mod. Phys. 81, 109 (2009))


(4) Unconventional quantum Hall effect, Andreev reflection
(5) Optical properties of graphene

A graphene-based broadband optical modulator

Transformation Optics Using Graphene

M. Liu et. al., Nature 474, 64 (2011)

The question:
Can we construct a nanostructure to control light similar to the graphene to control electrons?
2. Photonic monolayer graphene materials

(a) 2D systems
Diffusion behavior similar to the case in random medium

\[ T \propto e^{-\alpha L} \]

not \[ T \approx \text{constant} \]

\[ T \propto \frac{1}{L} \]

around Dirac point
Transmission coefficient

Frequency ($\omega a/2\pi c$)

$T \propto e^{-\alpha L}$

for gap

$T \approx \text{constant}$

for band

incident wave

PC slab
$T \cdot L \propto \text{constant}$  \quad \textbf{diffusion behavior}

Near Dirac point
Diffusion behavior
Corresponding to the gap region

Ballistic behavior

Why? The phenomenon originates from the crossed linear dispersion around the Dirac point.

Two linear resolutions of Dirac equation
Dirac Equation inside the sample

\[
\begin{pmatrix}
0 & -iv_D(\partial_x - i\partial_y) \\
-v_D(\partial_x + i\partial_y) & 0
\end{pmatrix}
\begin{pmatrix}
\Psi_1 \\
\Psi_2
\end{pmatrix}
= (\omega - \omega_D)
\begin{pmatrix}
\Psi_1 \\
\Psi_2
\end{pmatrix}
\]

Maxwell equation outside the sample

\[
(\partial_x^2 + \partial_y^2)E(x,y) + \frac{\omega^2}{c^2}E(x,y) = 0.
\]

Applying boundary condition of flux conservation

\[
j_H = j_D
\]

\[
j_D = v_D \Psi^* \sigma_x \Psi = v_D(\Psi_1^* \Psi_2 + \Psi_2^* \Psi_1)
\]

\[
j_H = \frac{\varepsilon_0 c^2}{4i\hbar \omega^2} \left( E^* \frac{\partial E}{\partial x} - E \frac{\partial E^*}{\partial x} \right)
\]

\[
T \propto \frac{1}{L}
\]

Sepkhanov, et. al

Some interesting phenomena can be observed

*Zitterbewegung* for photon and acoustic wave

valley beam splitter or collimator

Electromagnetic one-way edge modes analogous to quantum Hall edge states

Dirac cones induced by accidental degeneracy and zero-refractive-index materials

X. Huang et. al., Nature Materials 10, 582 (2011)
(b) Monolayer graphene consisting of metal spheres

dipole and quadrupole modes.

Dezhuan Han, et. al.,
Phys. Rev. Lett. 102, 123904 (2009)
(c) Monolayer acoustic graphene consisting of spheres

Steel spheres in air, $R=0.28a$

$\rho = 7670 \text{ kg/m}^3$

$c_l = 6010 \text{ m/s}$

$c_t = 3230 \text{ m/s}$

Rubber spheres in water with $R=0.2a$

$\rho = 1300.0 \text{ kg/m}^3$

$K = 2.20 \times 10^9 \text{ N/m}^2$

$G = 9.98 \times 10^6 \text{ N/m}^2$
Wei Zhong and Xiangdong Zhang,
3. Multilayer photonic graphene materials

(1) Multilayer graphene for electron

The electronic properties strongly depend on the stacking sequence.
The problem: can we find the similar phenomena for the photon?
(b) Multilayer photonic graphene

Three types of stacking: every layer consisting of metallic sphere, which the Drude-type permittivity

\[ \varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2} \quad \omega_p = 6.18 \text{ eV} \]

The radius of the sphere is 10nm; the lattice constant \( a=60\text{nm} \)
Multiple scattering method to calculate energy spectra of three-dimensional photonic crystal slab

\[
\tilde{E}_{sc}(\vec{r}) = \sum_{j=1}^{N} \sum_{l=1}^{\infty} \sum_{m=-l}^{l} \left[ \frac{i}{q} b_{jlm}^{E} \nabla \times \sum_{\vec{R}_n} \exp(ik \cdot \vec{R}_n) h_{l}^{+}(q_{r_{nj}}) \tilde{X}_{lm}(\vec{r}_{nj}) \right. \\
\left. + b_{jlm}^{H} \sum_{\vec{R}_n} \exp(ik \cdot \vec{R}_n) h_{l}^{+}(q_{r_{nj}}) \tilde{X}_{lm}(\vec{r}_{nj}) \right].
\]

\[
\tilde{E}_{j,sc}'(\vec{r}) = \sum_{l=1}^{\infty} \sum_{m=-l}^{l} \left( \frac{i}{q} b_{jlm}^{E} \nabla \times j_{l}(q_{r_{nj}}) \tilde{X}_{lm}(\vec{r}_{nj}) + b_{jlm}^{H} j_{l}(q_{r_{nj}}) \tilde{X}_{lm}(\vec{r}_{nj}) \right),
\]

\[
b_{jlm}^{P} = T_{jlm}^{P} \left( \sum_{j'=1}^{N} \sum_{P'=E,H} \sum_{l'm'} \Omega_{jlm,j'l'm'}^{P'} b_{j'l'm'}^{P'} + a_{jlm}^{0P} \right).
\]

\[
\det \left| \delta_{PP'} \delta_{jj'} \delta_{ll'} \delta_{mm'} - \sum_{l''m''P''} \Omega_{jlm,j''m''}^{P''} T_{jlm,j''m''}^{P'} \right| = 0,
\]

AAA stacking  N=2

ABA stacking (Bernal)

Parabolic $d=1.0a$

Corresponding electron system

ABC stacking
(Rhombohedral)

$d = 1.0a$

Corresponding electron system

• Similar energy spectra for the electron in multilayer graphenes have been observed for the photon in the present photonic graphene structures.

• This means that the transport properties of light similar to the case of electrons in multilayer graphene can be realized by constructing photonic nanostructures.

• Our findings provide a way to control the transport of light similar to the multilayer graphene for electrons.
4. Dirac-cone photonic surface states

(1) Topological insulator for electrons

Dirac-cone surface state
topological insulator

The number of holes is called “genus” in topology.
(2) Dirac-cone photonic surface states

3D photonic crystal slab in diamond [111] planes with 7 monolayers, every monolayer consisting of metallic spheres coated by dielectric layer.

The metallo-dielectric spheres
The type I surface coating layer is 2% in radius.
The coating layer is radius 10% in radius

**Phys. Rev. Lett.**

105, 036404

Wei Zhong and X. Zhang, Optics. Express 19, 23738 (2011)
The thickness of the dielectric coating 10%, 20%, 30%, 40%, 50%, 60% and 65% of the sphere radius
3D PC
High
16
Layers, length (10a)
width (11a)
NA=0.3

Guide mode
Mode gap
Dirac point

Wei Zhong and Xiangdong Zhang, Optics. Express 19, 23738 (2011)
5. Probing photonic surface states by STEM

STEM (or EELS) and Dielectric Materials

STEM: scanning transmission electron microscopy
The basic principle of STEM is that we can obtain some information of dielectric material from electron energy loss spectroscopy (EELS).

The interaction between a moving charged particle (Ze) with velocity $V$ and dielectric materials
Recent investigations have shown that some unusual properties of linear metamaterials can be explored by STEM or EELS.

\[ \Delta E = \int dt \vec{v} \cdot \vec{E}^{sc}(\vec{r}_i, t) = \int_0^\infty \omega \, d\omega \, P(\omega). \]

\[ P(\omega) = \frac{1}{\pi \omega} \int dt \, \text{Re}\{e^{-i\omega t} \vec{v} \cdot \vec{E}^{sc}(\vec{r}_i, \omega)\}. \]
6. Summary

1. We have developed the multiple scattering method to study energy spectra and surface states of 3D phononic crystal slab.

2. We have demonstrated multilayer photonic graphene and found Dirac-cone photonic surface states, they can be probed by STEM.
Other related works

(1) Second harmonic generation and nonlinear Smith-Purcell effect

J. Xu and Xiangdong Zhang, Optics Express 20, 1669 (2012)
J. Xu and Xiangdong Zhang, Optics Express 19, 22999 (2011)

(2) Photon entangled states by nonlinear photonic crystal

Y. Dong and Xiangdong Zhang, Optics Express 16, 16962 (2008)
Y. Dong and Xiangdong Zhang, J. Optics 13, 035401 (2011)
(3) Unusual light spin Hall effect

(4) The holographic method to fabricate the circular photonic crystals and microlaser

(5) Correlated optics and ghost image
Experimental Observation of Quantum Talbot Effects


Thanks for your attention!